

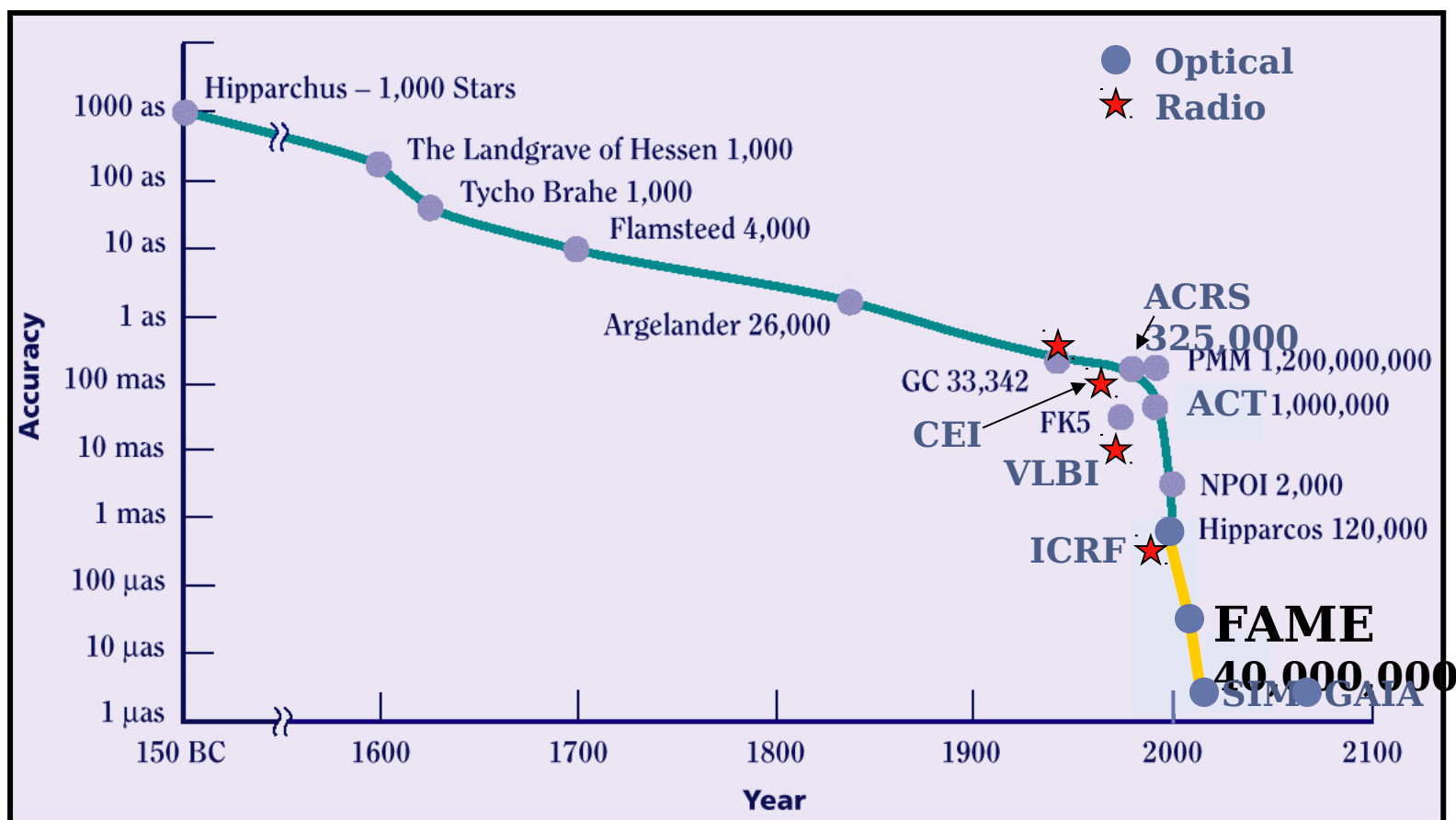


The Full-sky Astrometric Mapping Explorer

**Kenneth J. Johnston
Principle
Investigator**



The Golden Age of Astrometry



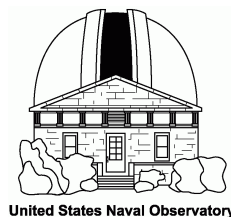
FAME

Full-sky Astrometric Mapping Explorer





Full-sky Astrometric Mapping Explorer



United States Naval Observatory

PI, Oversight of science and budget, MO&DA Lead, GDS, MOC, & SOC development and implementation, E/PO Lead



Naval Research Laboratory

PM, System Engineering, S/C bus development, integration, & test, Comprehensive testing

Lockheed Martin Missiles and Space



Instrument design, fabrication, testing, & support

Smithsonian Astrophysical Observatory

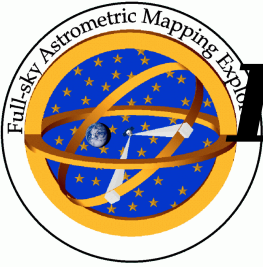
PS, Synthesis and verification of scientific measurement system, E/PO support





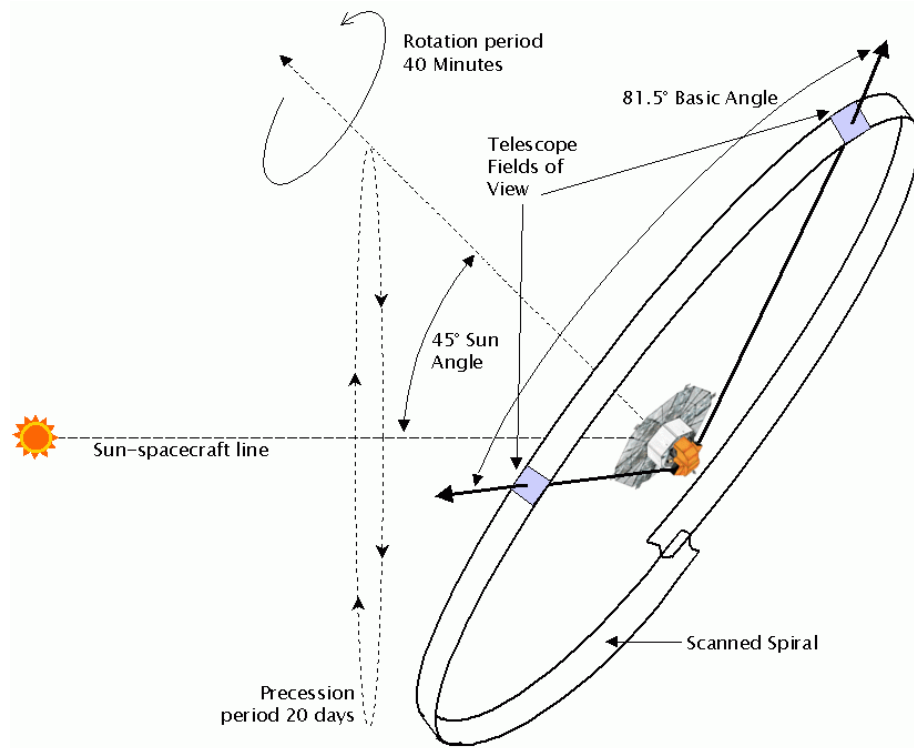
Technical Goals and Objectives of FAME

- ◆ **FAME will perform an all sky, astrometric survey with unprecedented accuracy**
 - **Upgrades existing star catalogs by providing a precision catalog of 4×10^7 Stars**
 - **Provides positions of bright stars ($5 < m_v < 9$) to $< 50 \mu\text{as}$**
 - **Provides positions of fainter stars ($9 < m_v < 15$) to $< 500 \mu\text{as}$**
 - **5 year extended mission allows for accurate measurement of stellar parallax, proper motions, and monitoring of stellar variability**
 - **Photometric data in four Sloan DSS bands (g' , r' , i' , z')**



FAME Mission Description

- **The telescope has two fields-of-view separated by a 81.5° basic angle**
- **The spacecraft will rotate with a 40 minute period with the apertures sweeping out a great circle on the sky**
- **The spacecraft rotation axis is at a 45° angle to the Sun**
- **The solar radiation pressure on the solar shield results in precession about the Sun-spacecraft line with a 20 day period**
- **The spacecraft is in Geosynchronous orbit for continuous contact**

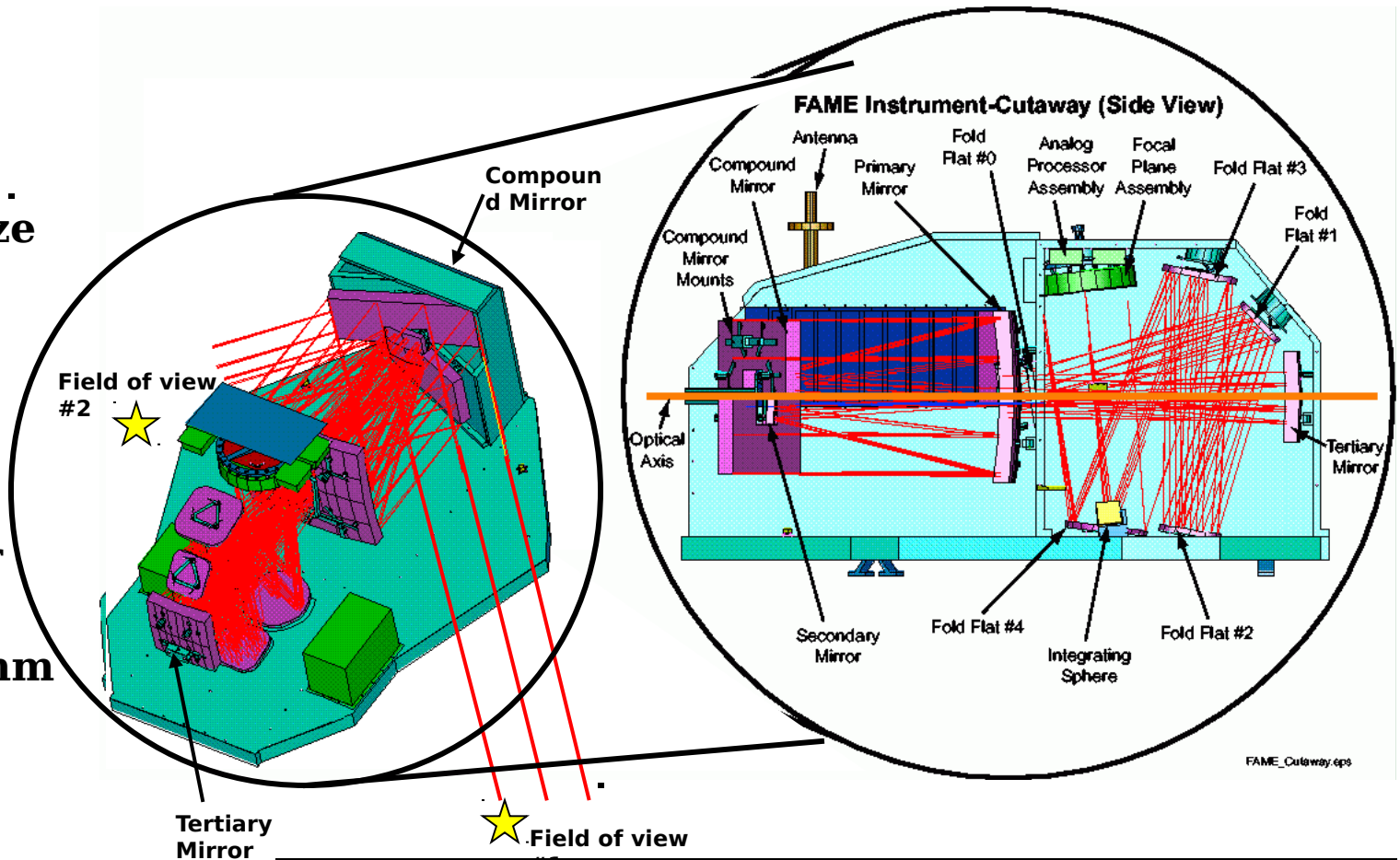


The FAME observing concept - The axis of the FAME spacecraft is pointed 45° from the Sun and precesses around the Sun with a 20 day period. The FAME spacecraft rotates with a 40 minute period. The two fields of view are normal to the rotation axis and are separated by a 81.5° degree basic angle.



FAME Instrument Description

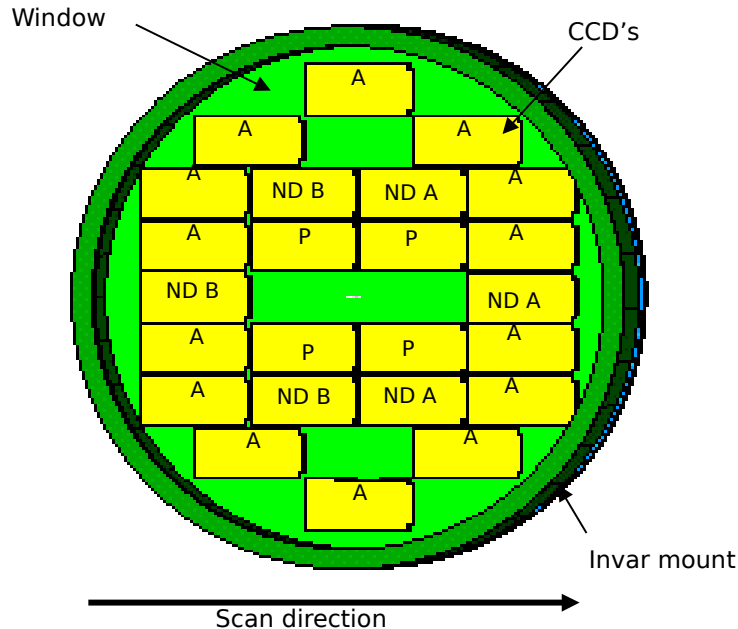
- ◆ Two input apertures
- ◆ 60×25 cm . aperture size (each)
- ◆ Total mass
- ◆ 229 kg
- ◆ Total power
- ◆ 272 W
- ◆ 400 to 900nm spectral range
- ◆ Back illuminated CCDs



- ◆ Instrument developed by Lockheed Martin Missiles and Space ATC

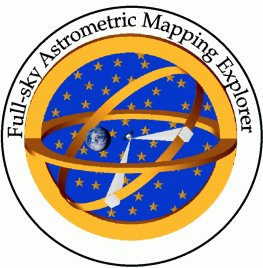


FAME Instrument Description



The FAME focal plane - 24 2k · 4k CCDs arranged around a 1.1° diameter field of view. Devices marked with 'P' are the 4 photometric CCDs and devices marked with 'A' are the 20 astrometric CCDs. The 6 devices marked with 'ND' have neutral density filters for astrometry of brighter stars.

- ◆ **Telescope produces images of Stars using 24 large format CCDs**
 - Images of stars are continually traversing CCD array as the spacecraft rotates
 - CCDs use time delay integration
 - Synchronization of CCD clock rate and image motion is assured via rotation rate sensors
 - Star images are time tagged, windowed, and transmitted to Earth.
 - **6 CCDs are covered by neutral density filters for astrometry of bright stars**



FAME Error Sources

CCD characteristics

read noise

dark current

non-linearity

charge transfer inefficiency

**deterioration of CTE from radiation
damage**

variations in the CCD flatness

pixel-to-pixel gain variations

sub-pixel gain variations

wavelength dependent gain variations

CCD defects

CCD pixel registration errors

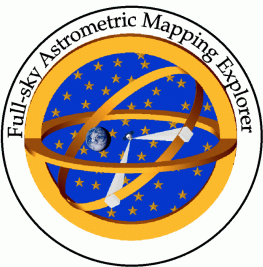
color dependent penetration of photons

recovery from saturation

CCD clock cross-talk

CTE behind bright stars

ADC errors



FAME Error Sources

(continued)

Instrument alignment

point-spread function (PSF)

PSF variations with position in field

misalignment of the CCD column with the rotation

variation of plate scale across field

Instrument stability

PSF variations with time

errors in CCD clock rate relative to rotation

error in determination of rotation rate

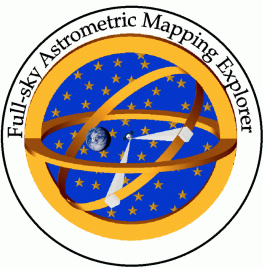
error in setting the clock speed

Variations in telescope structure

thermal

evaporation

Variation in basic angle



FAME Error Sources

(continued)

Photon statistics

Spacecraft

CCD/window contamination

**aberration due to error in knowledge of
S/C velocity**

Stellar/External

saturation

stellar activity

stellar companions

incorrect stellar model

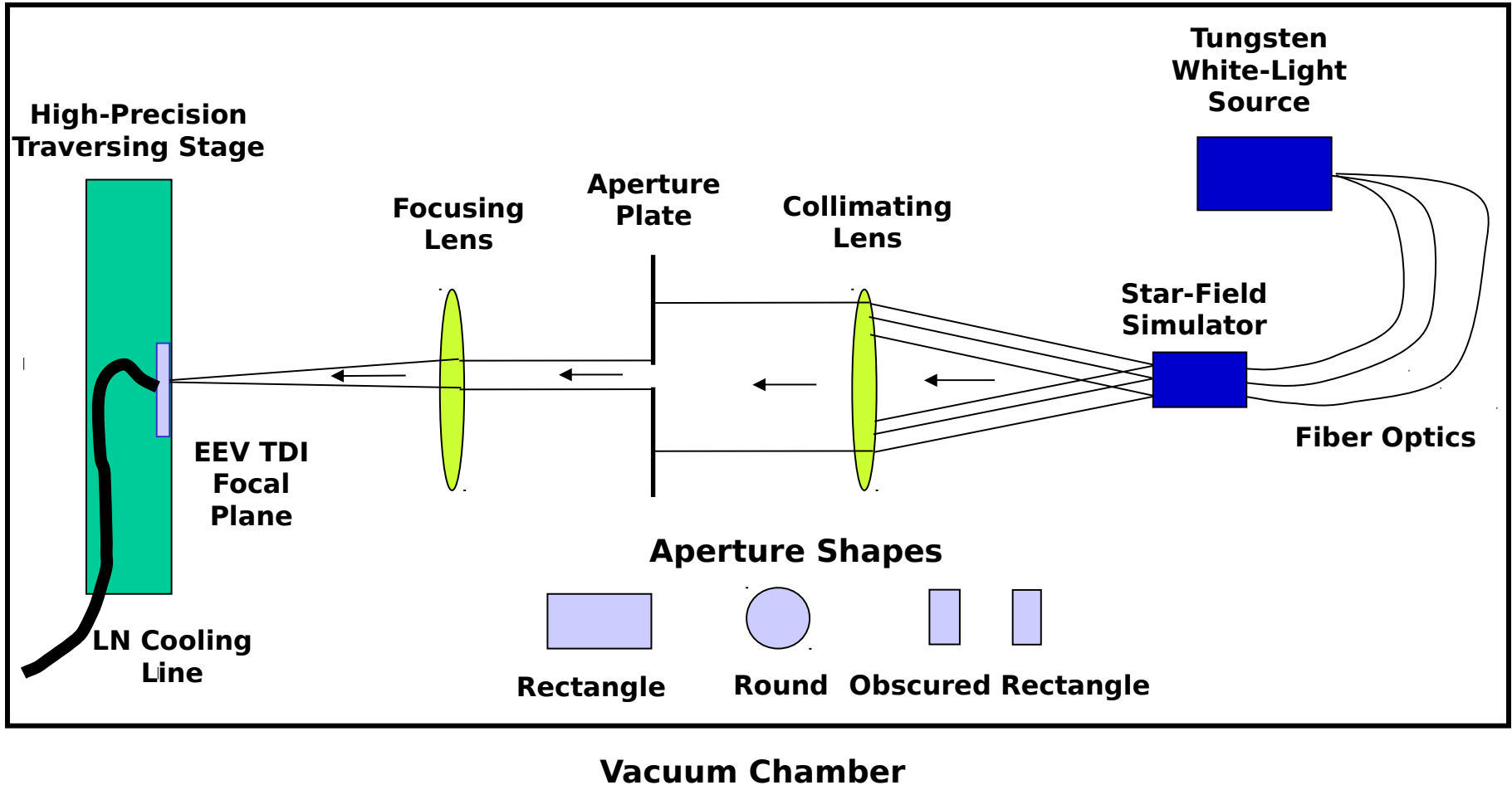
confusion

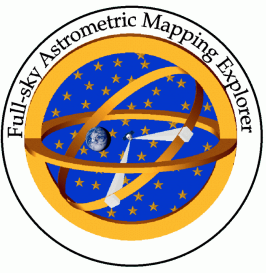
cosmic rays

scattered light



CCD Image Centering Experiment Layout



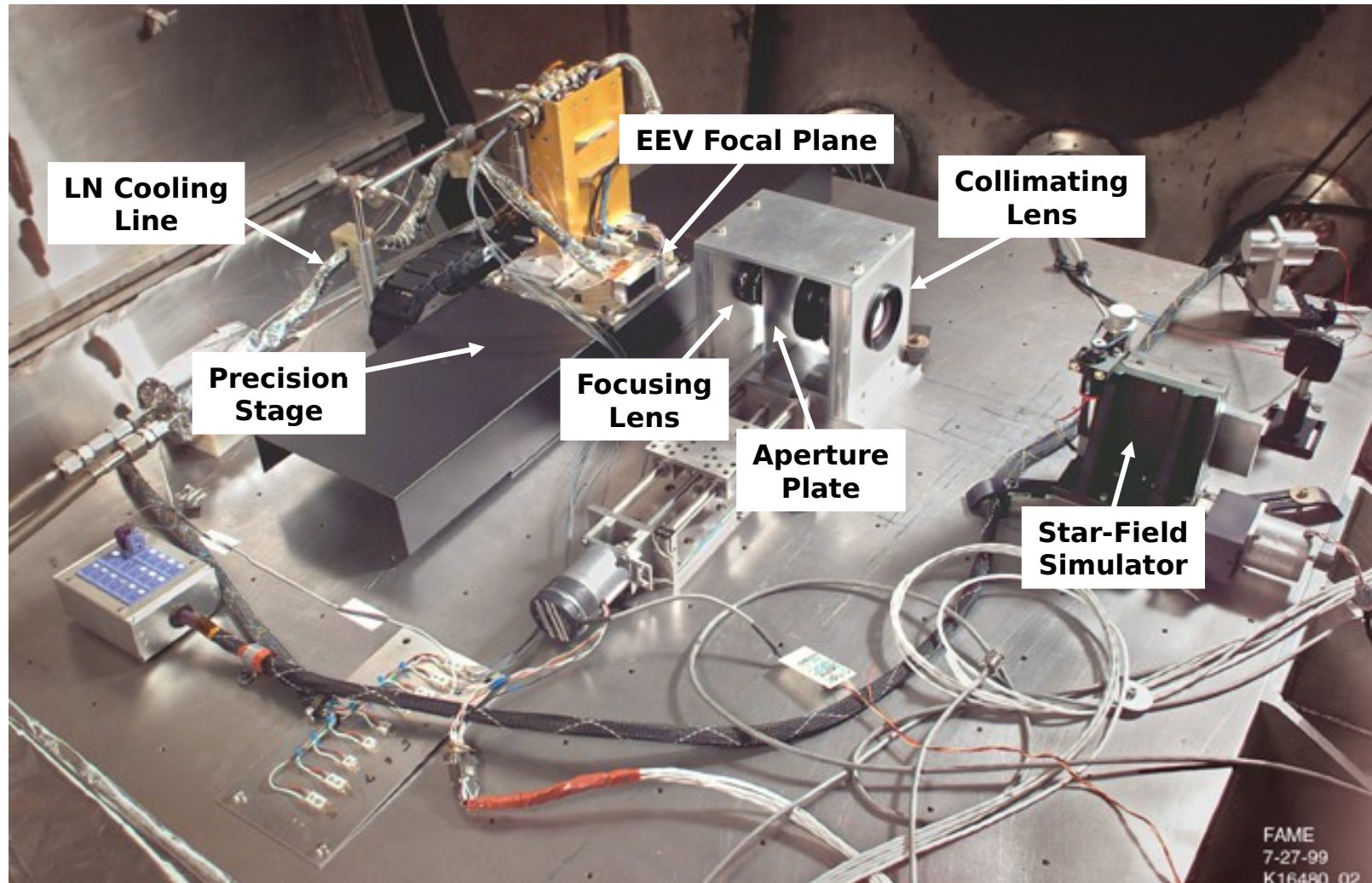


CCD Image Centering Results To Date

- **Centroiding accuracy achieved**
 - **Demonstrated $< 1/350$ pixel accuracy**
 - **Potentially as good as $1/500$ pixel**
- **Developed data-base for operating EEV focal plane in TDI mode for FAME instrument**
- **Developed & tested new centroiding algorithms applicable to FAME data processing**



CCD Image Centering Experiment Hardware





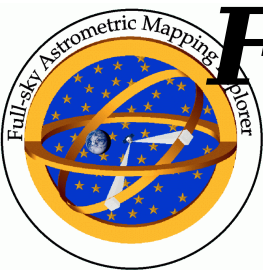
Fame Error Sources

- ▢ **CCD characteristics**
 - ▢ Read noise, QE variation, etc.
- ▢ **Instrument alignment**
 - ▢ PSF variations
- ▢ **Instrument stability**
 - ▢ Thermal effects
- ▢ **Spacecraft**
 - ▢ Knowledge of spacecraft velocity
- ▢ **Stellar/external**
 - ▢ Photon statistics



FAME Estimated Error Budget

Error Source	Error (μas) a priori	Error (μas) a posteriori
Photon Statistics		
$m_V=9$	540	540
$m_V=15$	10800	10800
Read Noise ($7e^-$ rms, $m_V=9$)	6600	6600
QE Variation	560	<10
λ -dependent absorption in CCD	300	30
Charge transfer effects	800	80
Incorrect Stellar Spectrum Model	4000	50
Undetected Companions	60	60
Onboard clock error	<100	<1
Telescope geometry variations	100	<10
Optical Distortion	2000	20
Refraction in CCD window	1	<1
Rotation Rate Changes	10^6	25
Ephemeris (1cm/sec knowledge)	7	<1



FAME Estimated Error Budget Totals

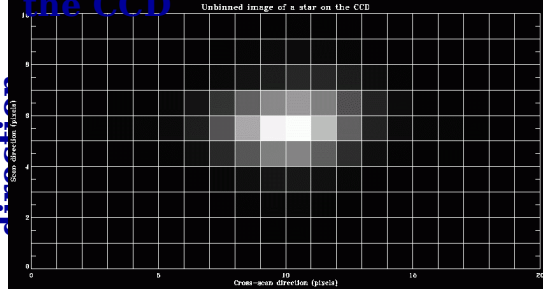
Visual Magnitude (m_V)	ND Filter Accuracy* (μas)	Gated Array Accuracy* (μas)
5	49	14
7	49	14
9	24	14
11	56	28
13	146	70
15	443	208

***Assumes systematic error contribution**

The FAME accuracy is 10 μ as - The predicted accuracy of FAME as a function of visual magnitude (m_V). The second column shows the accuracy if neutral density filters over 3 of the astrometric CCDs are used for astrometry of the brighter stars (baseline design). The third column shows the accuracy if the CCDs are only integrating during part of the time when a bright star is traversing the device

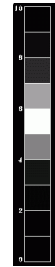
On-board data processing

Unbinned image of a star on the CCD



On-chip binning

scan direction
n



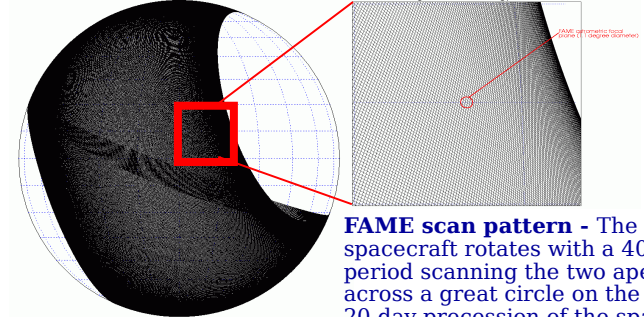
scan direction
n

Pixels in the cross-scan direction

- ✦ The data from most stars are binned by 20 in the cross-scan direction on the CCD before being read-out

Sphere Reconstruction

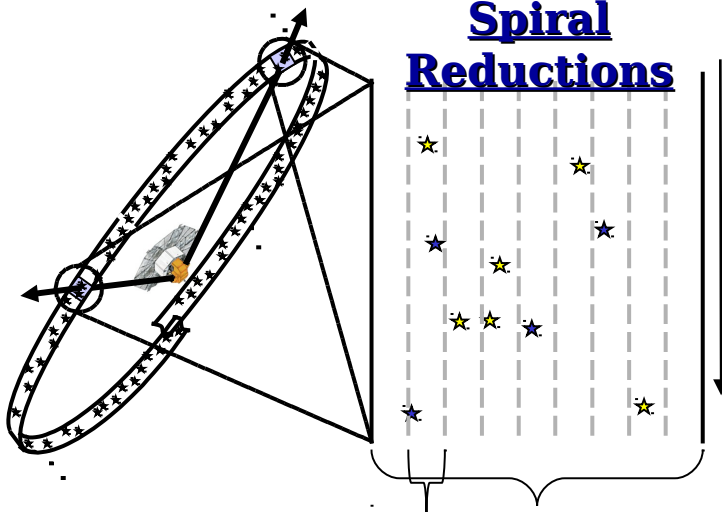
FAME scanning pattern over a 20 day period



FAME scan pattern - The FAME spacecraft rotates with a 40 minute period scanning the two apertures across a great circle on the sky. The 20 day precession of the spacecraft about the Sun-spacecraft line results in FAME covering the entire sky except for exclusion zones within 45° of the Sun and the anti-Sun direction every 20 days.

- ✦ Use a subset of the stars to globally tie the spirals together into a sphere

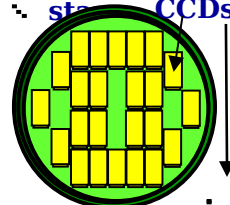
Spiral Reductions



Width of Scan for a single column of CCDs

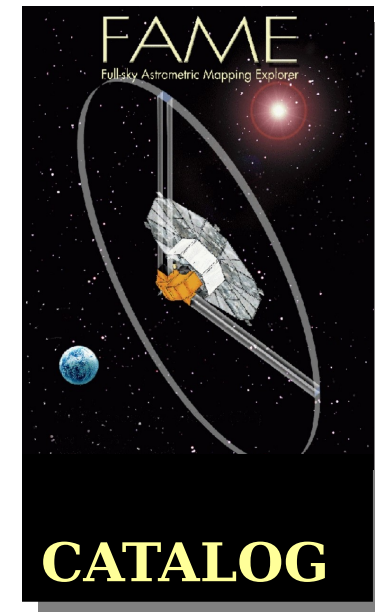
Width of Scan (entire FAME FoV)

Star from the same field of view as the target star
Star from the field of view 81.5° away from the target star
CCDs



Focal Plane Assembly

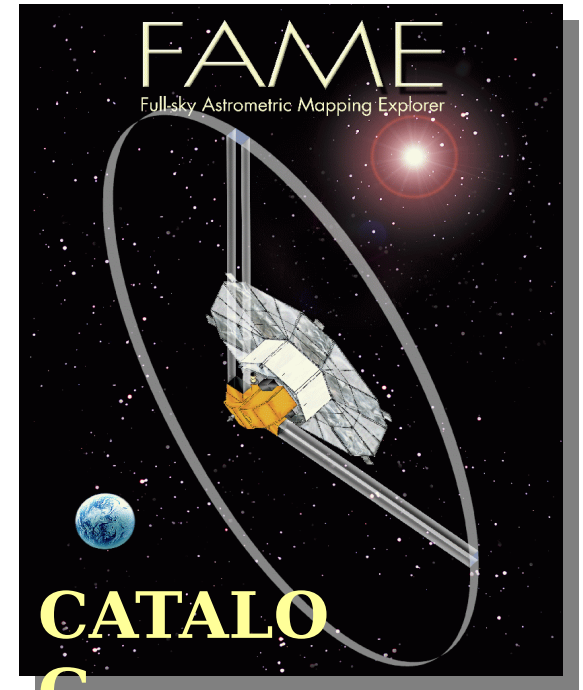
scan direction





FAME Catalog

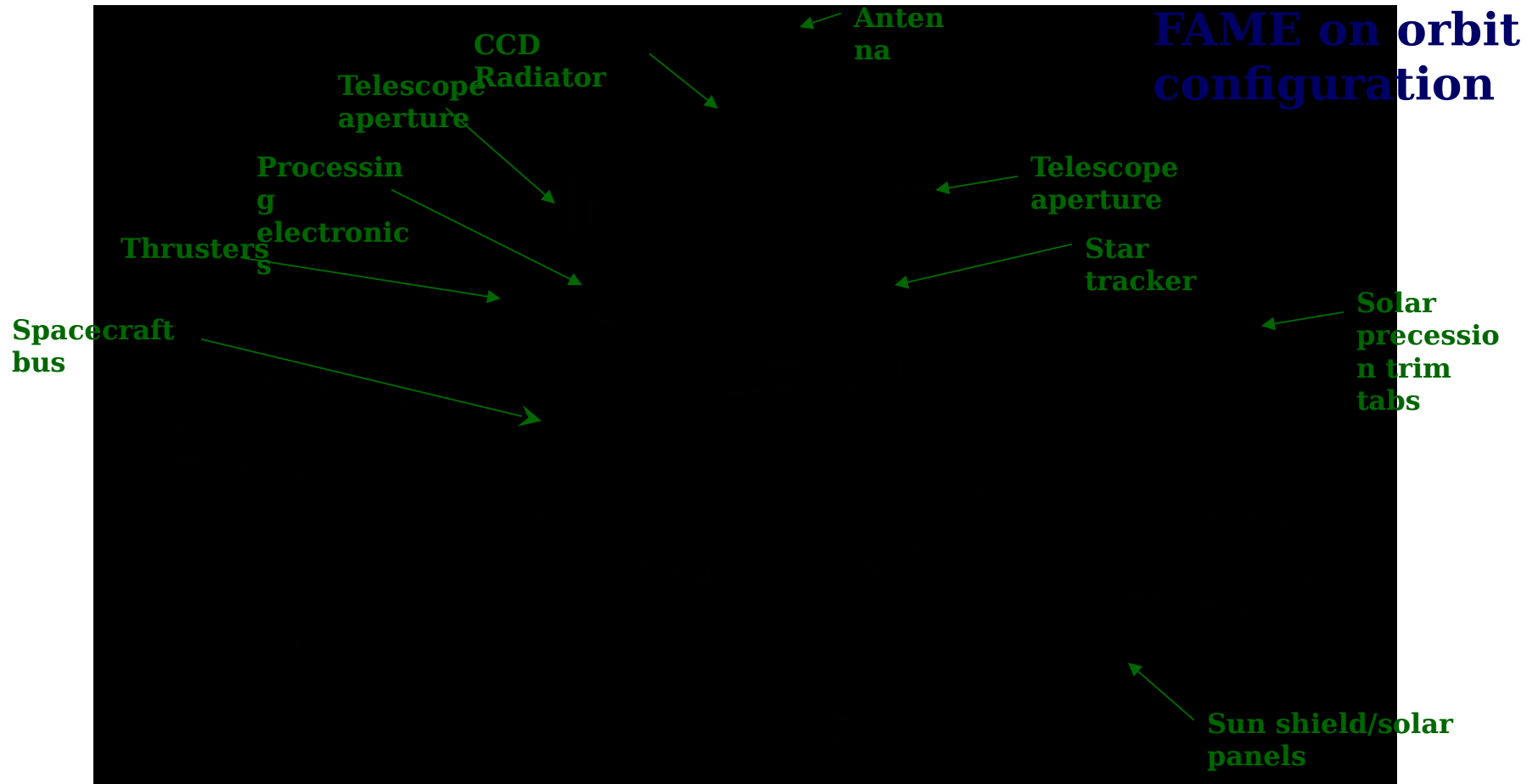
- ❑ **Catalog available 3½ years after launch**
- ❑ **Complete catalog from the extended mission available 6 years after launch**
- ❑ **90-95% of FAME customers will want the complete catalog with nominal positions, parallaxes, proper motions, and photometry**
- ❑ **The other 5-10% will be interested in variations of a subset of the catalog over time**



The study of fundamental properties of a large sample of stars is needed to answer many key astrophysical questions



FAME Spacecraft



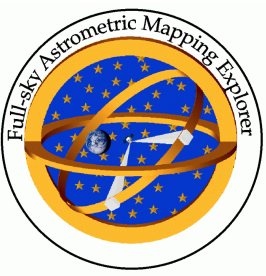
Spacecraft design uses component heritage from Clementine



FAME Schedule

- Phase A Concept Study
 - February - June 1999
- Phase B
 - September 2000 - September 2001
- Phase C
 - October 2001 - June 2002
- Phase D
 - July 2002 - October 2004
- Launch
 - October 2004
- Phase E
 - November 2004 - May 2008
- DoD Extended Mission
 - June 2007 - November 2010





Most Important Science Result

FAME opens up a new dimension in stellar astrophysics

- ▮ Stellar evolution and structure: calibration of absolute luminosities**
- ▮ Extragalactic distance scale: determine distances to “standard candle” stars which are fundamental in defining distance scales**
- ▮ Measure the distance to the Magellanic clouds to 2% accuracy**
- ▮ Determine the abundance of dark matter in the galactic disk**
- ▮ Discover brown dwarfs and giant planet companions**
- ▮ Statistically determine the level of optical variations in solar type stars**

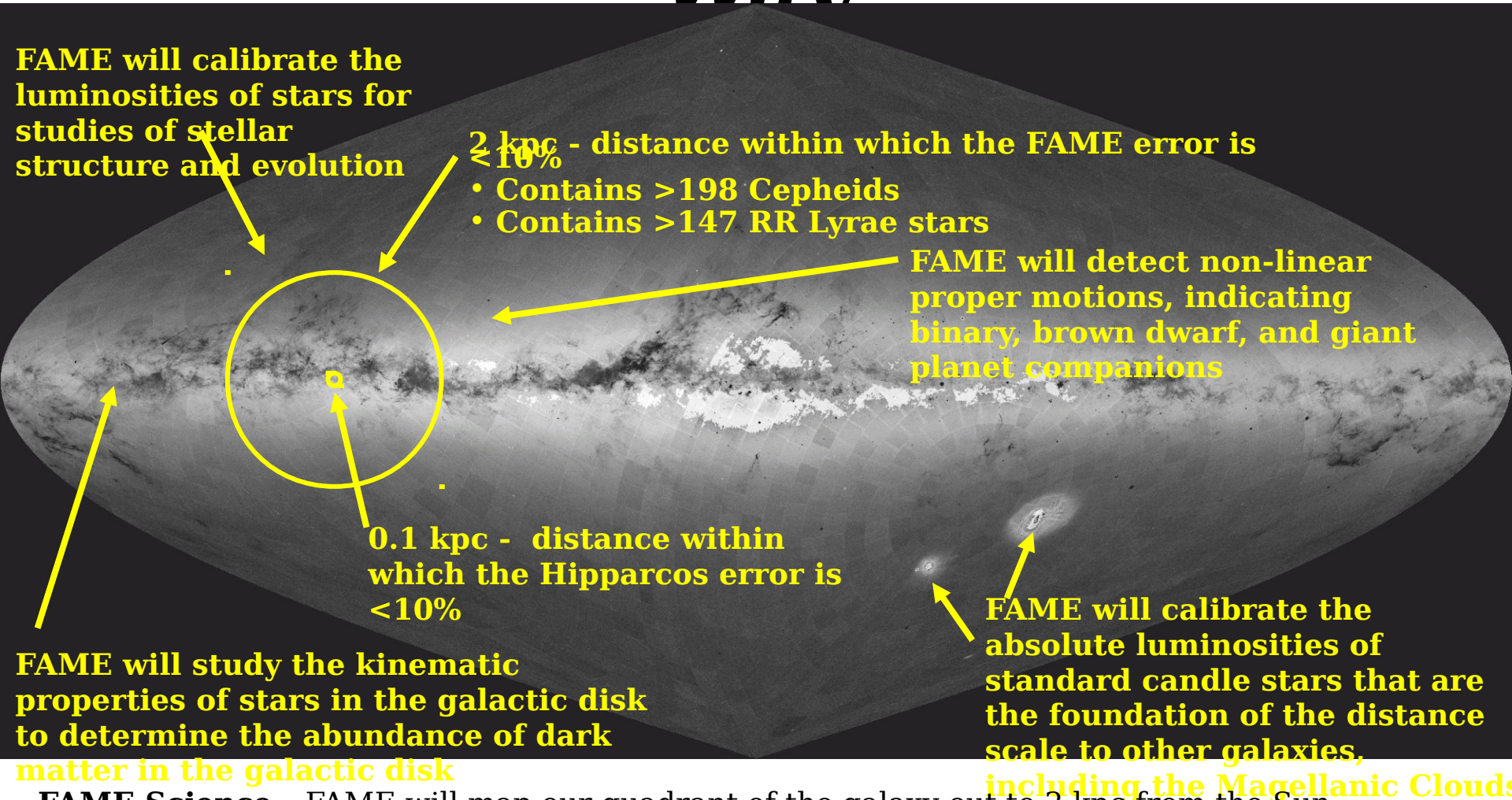


Most Compelling Science Driver

Large data set sampling ALL types of stars!

- **Occurrence of large planets for all types of stars**
- **Very large sample of stars for evolution studies by determining absolute luminosities**
 - **Open clusters**
 - **Globular clusters**
 - **Cepheids and RR Lyrae Stars**
- **“Zero point” calibration of the distance scale to 1%**

FAME Coverage of the Milky Way



FAME Science - FAME will map our quadrant of the galaxy out to 2 kpc from the Sun providing the information needed to calibrate the standard candles that define the extragalactic distance scale, calibrate the absolute luminosities of stars of all spectral types for studies of stellar structure and evolution, and detect orbital motions caused by brown dwarfs and giant planets. FAME will not only improve on the accuracies of star positions determined by Hipparcos but also expand the volume of space for which accurate positions

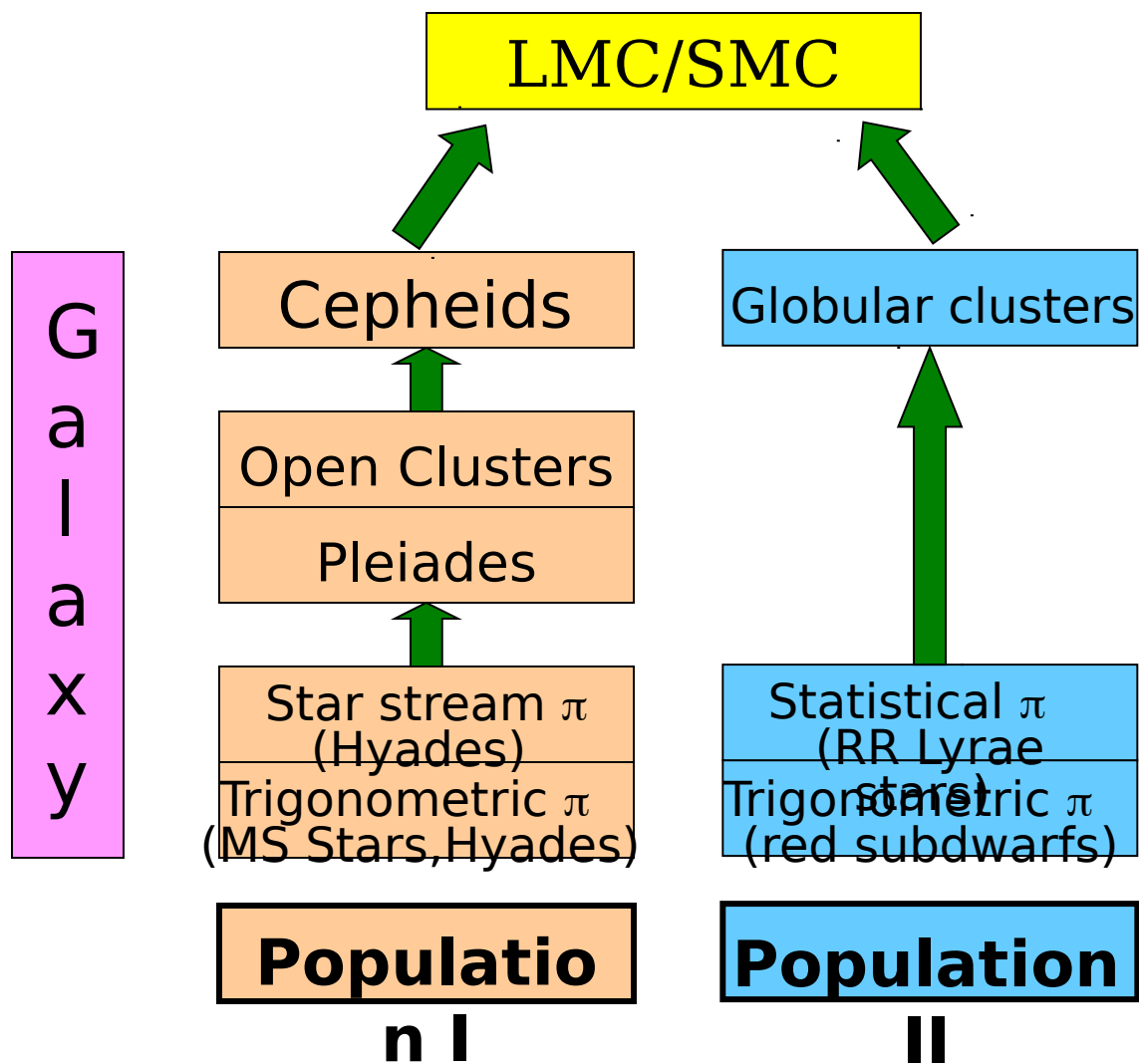


Answers to Fundamental Questions

- **Distance scale of the Universe**
 - “Zero point” calibration of the distance scale to 1%
 - Resolve distance to the LMC
 - Cepheids, globular clusters, and HB stars vs. RR Lyrae and red clump stars
- **Meaningful statistical sample of stars for companions with $m > M_{\text{jup}}$**
- **More accurate statistics on multiple vs. single star systems**
- **Survey of 40,000 solar-type stars to 0.001 mag. over a 5 year period**



The Distance Ladder (lowest part)





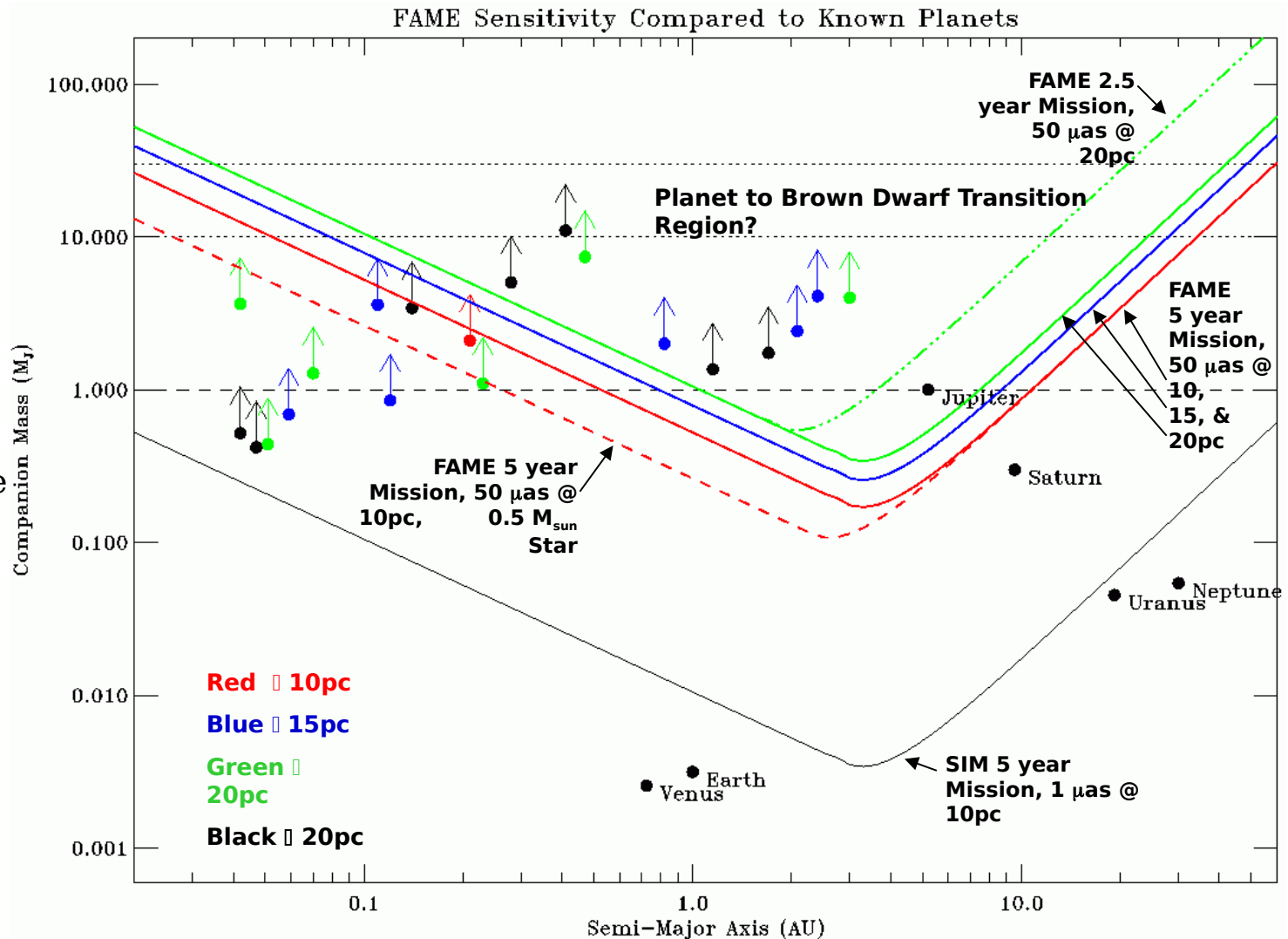
Astronomical Search for Origins and Planetary Systems (ASO)

- ▮ **Detect hundreds of sub-stellar companions of solar type stars**
- ▮ **Determine the inclinations and thus the masses of known exoplanets detected by radial velocity techniques**
- ▮ **Determine the frequency of solar-type stars orbited by brown dwarf companions in the mass range of 10 to 80 M_{jup} with orbital periods up to twice the duration of the FAME mission**
- ▮ **Explore the transition region between brown dwarfs and giant planets, which appears to be in the range of 10 to 30 M_{jup}**
- ▮ **Identify interesting targets for SIM and TPF**



FAME Planet Detection Sensitivity

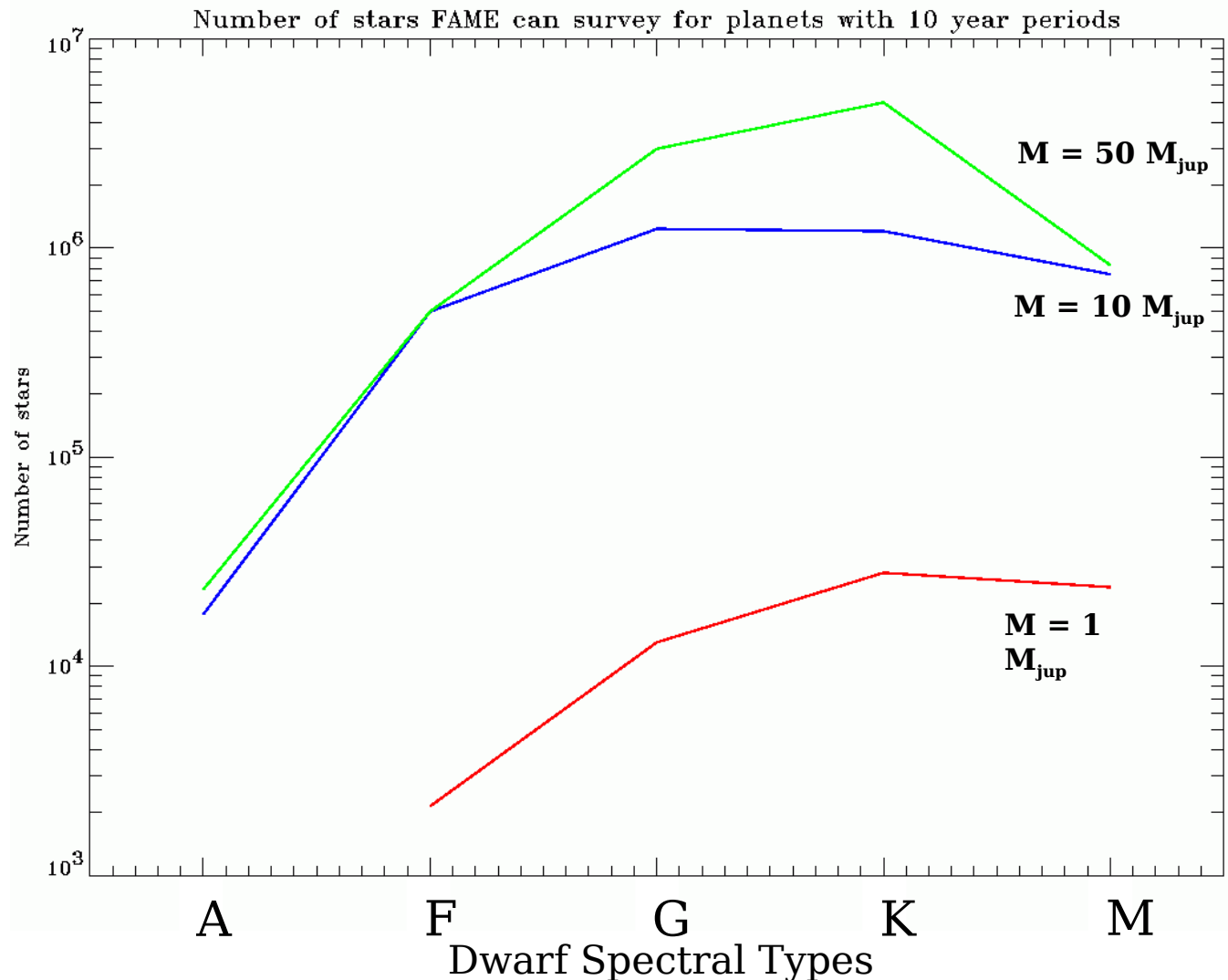
FAME planet detection sensitivity - The precision of FAME is compared to the known exoplanets and the SIM predicted precision. The masses of the known planets are minimums because the inclination of the systems are unknown. The points and arrows are color coded to indicate the approximate distance of the system. The FAME sensitivities are plotted for stars at 10 (red), 15 (blue), and 20 parsecs (green) for a host





FAME Planet Survey

FAME planet survey - FAME will survey a substantial number of stars for giant planets, giving a statistically significant sample of giant planet masses and frequency of planet formation. This figure shows the number of stars within the precision range of FAME that can be sampled for the given main sequence spectral types. This figure assumes a 10 year orbital period for the planet.



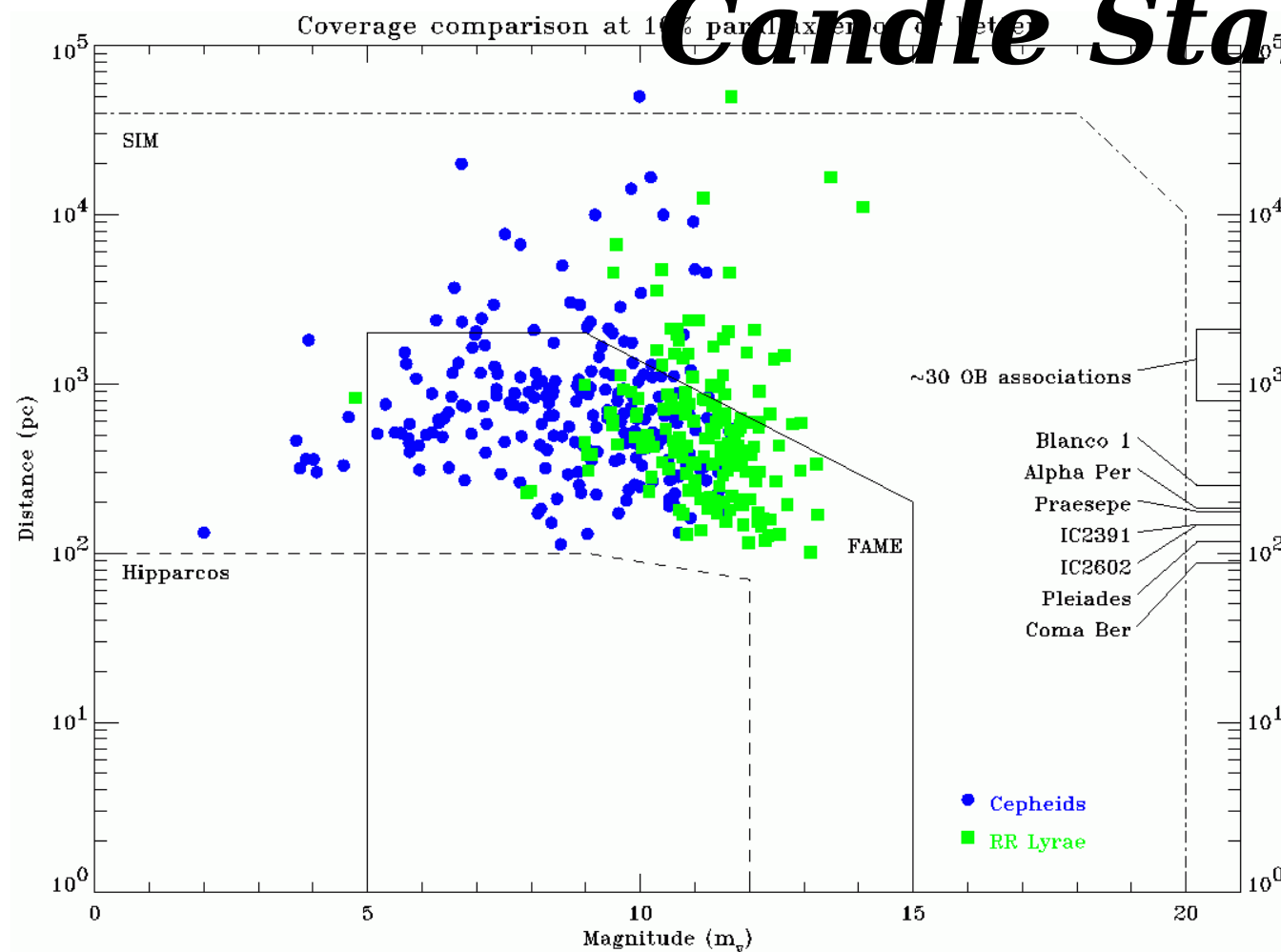


Structure and Evolution of the Universe (SEU)

- **Knowledge of stellar properties of our galaxy**
- **Zero point of the distance scale to 1%**
- **Distribution of matter (both luminous and dark) in the disk of our galaxy**
- **Insight into how both dark and luminous matter determine the geometry and fate of the Universe**

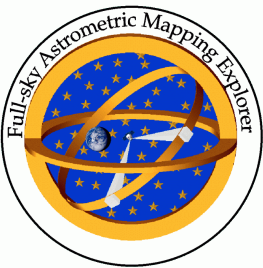


Distance/Magnitude Limits and Standard Candle Stars



FAME observations of standard candle stars -

For standard candle stars to serve as the foundation of the extragalactic distance scale, distances to the nearby stars need to be accurately determined. Hipparcos did not determine distances to these stars with a high level of accuracy. FAME is designed to determine distances accurate to 10% error or better to a large sample of Cepheids and RR Lyrae stars, thus refining the extragalactic distance scale. While SIM may obtain distances to some of these stars to better accuracy, SIM is a pointed mission that will



Stellar Evolution

- ▮ **Calibrate the absolute luminosities of solar neighborhood stars**
 - ▮ **Population I**
 - ▮ **Population II**
- ▮ **Enable diverse studies of stellar and galactic evolution**
- ▮ **Determine distances and ages of galactic open and globular clusters using the determined absolute luminosities**
- ▮ **Resolve the discrepancy in distances to the Pleiades and other open clusters**



Open Clusters are Key to Testing Stellar Theory

- **Theorists estimate their models are uncertain at the 0.02 mag. level, but disagree with one another at the 0.04 mag. Level**
- **FAME will determine the distances to all clusters within 200pc to 1% or better**
 - Nearby clusters - FAME will measure distances to individual stars to take out depth effects
 - More distant clusters - FAME will determine relative depths of stars from differences in proper motions

Cluster	~Distance, d (pc)	Transverse velocity, V_t (km/s)	Velocity dispersion, V_d (m/s)	Radius (degrees)	$\frac{V_d}{V_t}$	$\frac{300\mu\text{as/yr}}{V_t/d}$
Hyades	46	25	330	2	1.3%	0.3%
Pleiades	130	30	700	2	2.3%	0.6%
α Per	180	35		2		0.7%
Preasepe	180	33	600?	4	1.8%	0.8%
Coma	80	6	300	3	5.0%	1.9%
Ursa Major	20	11		20		0.3%
IC 2391	145					
IC 2602	145					



The Sun-Earth Connection (SEC)

- ▮ **By monitoring ~40,000 solar-type stars for 5 years, FAME can dramatically increase the number of solar-type stars available for accurate variability studies by a factor of 100. FAME can:**
 - ▮ Sample long-term behavior of solar-type stars, with possible implications for climate changes or conditions inimical to life
 - ▮ Search for evidence of magnetic activity cycles analogous to the 11 year solar activity cycle
- ▮ **Sample the activity cycles of other solar type stars so we can put the Sun's activity level in the context of other, similar stars**
- ▮ **Identify and categorize a large number of variable stars**



Precise Photometric Survey for Magnetic Cycle Variability

Expected Photometric Uncertainty (single

Magnitude	Astrometric Filter	observation	Filters	Hipparcos H_p
8	0.0010	0.0016		0.011
9	0.0016	0.0025		0.015
11	0.004	0.006		0.033
13	0.010	0.016		
15	0.025	0.040		

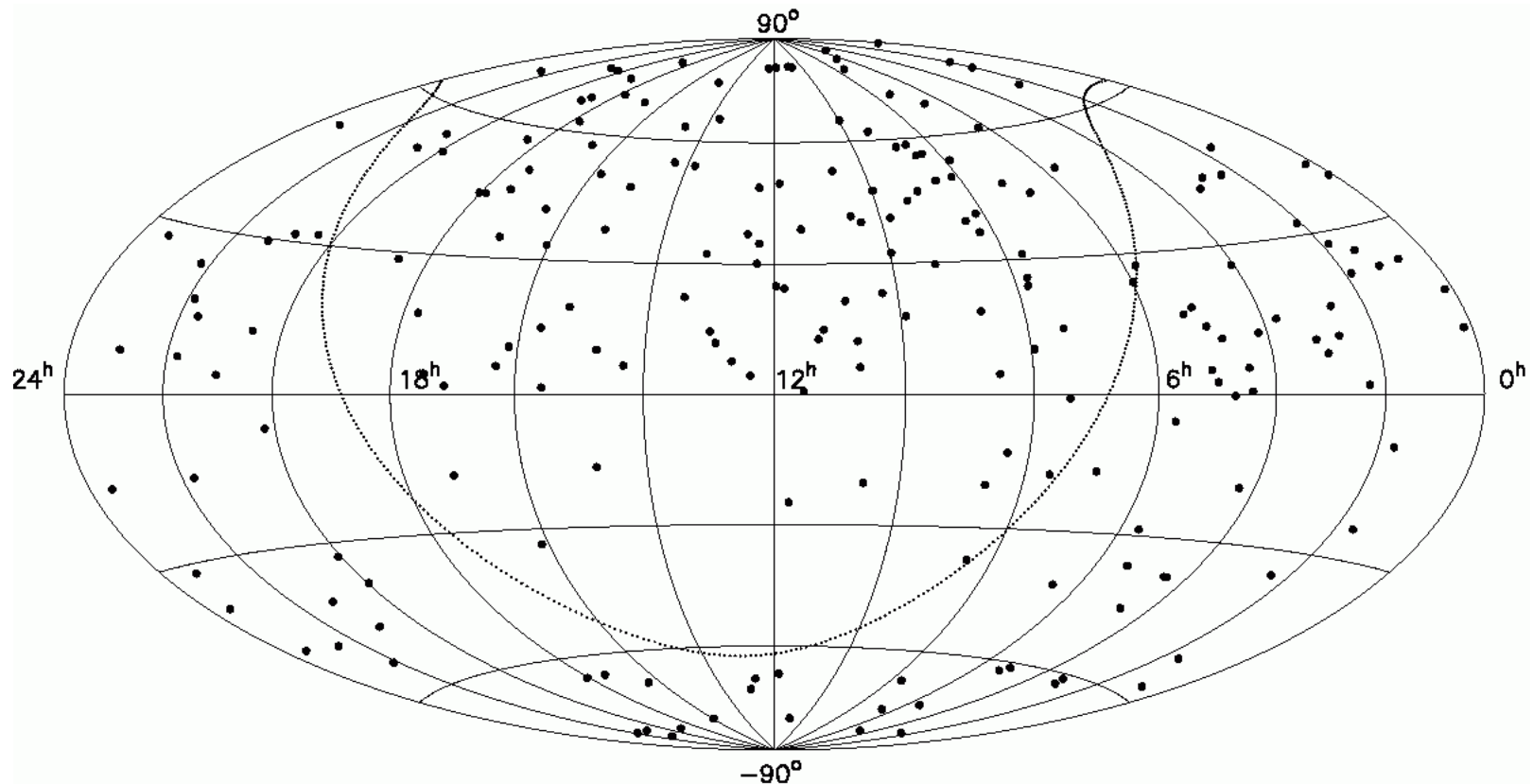
**Number of stars to be surveyed by FAME (50 μ as at mag.
= 10.0)**

Luminosity Class	O	Total = 500,000			G	K	M0
I, II, III				3700	30000	50000	20000
V	45	130000	50000	130000	40000	9000	1170
White Dwarf		25	10				

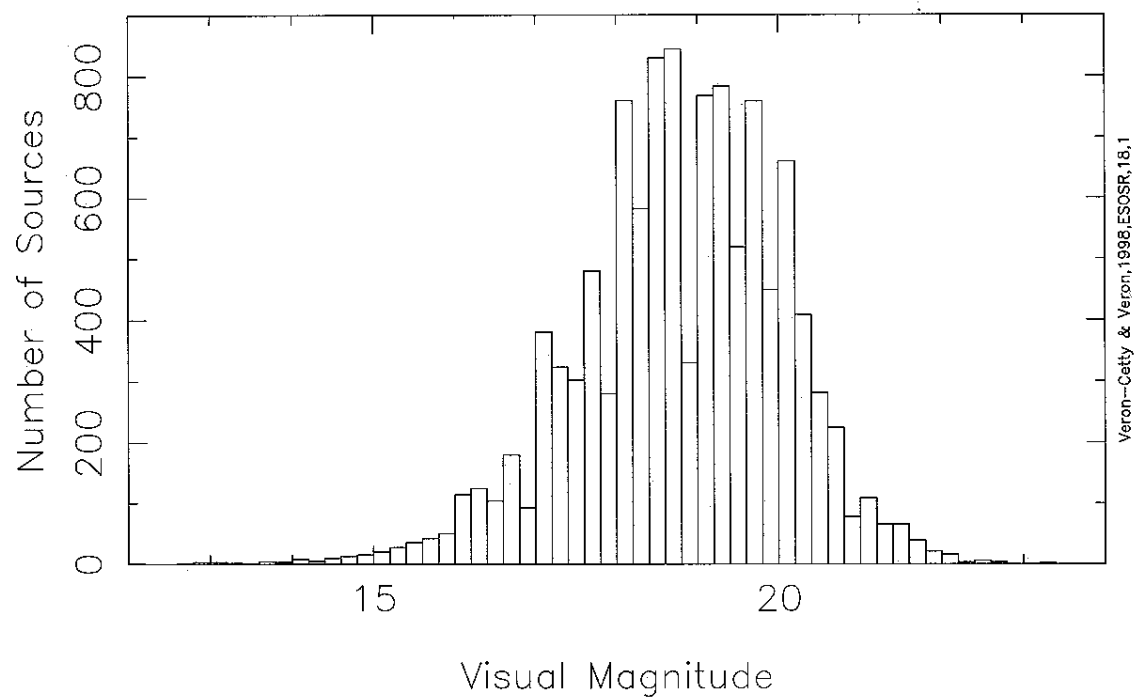
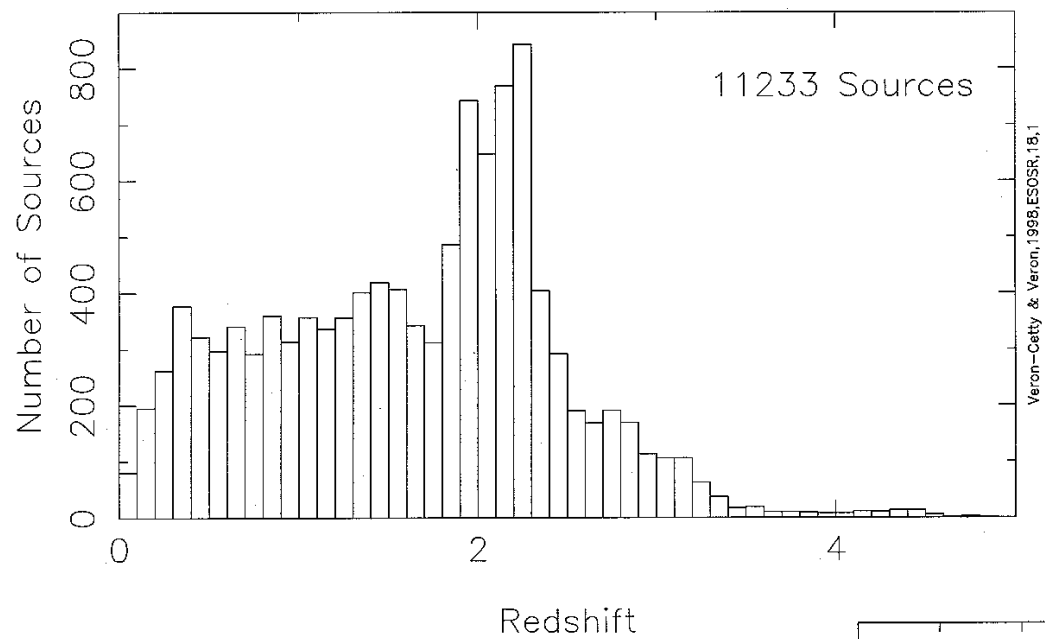


Radio Reference Frame

- **ICRF adopted in 1998**
- **Individual source positions to 300 μ as**



Quasars and BL Lac Objects





FAME Astrometric

Accuracy:

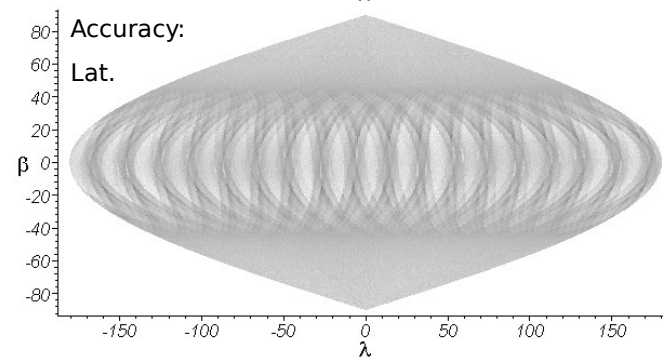
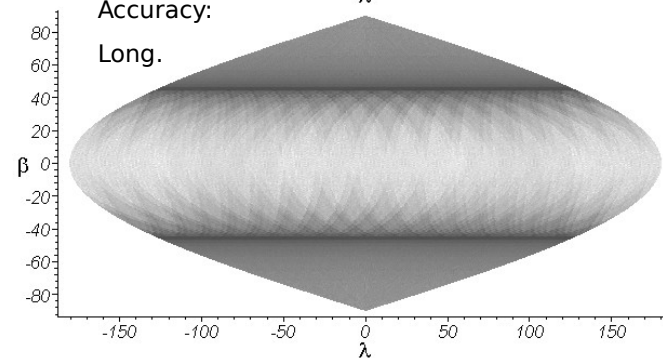
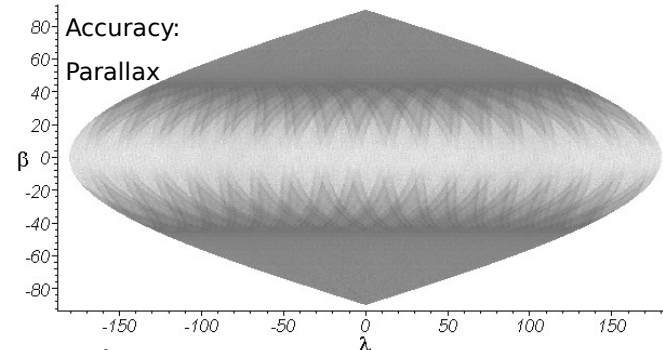
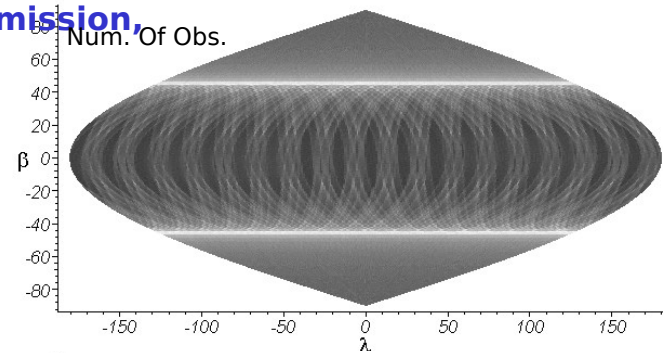
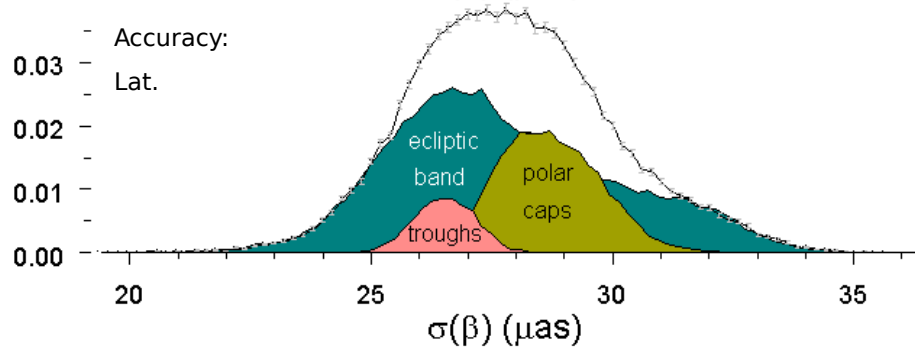
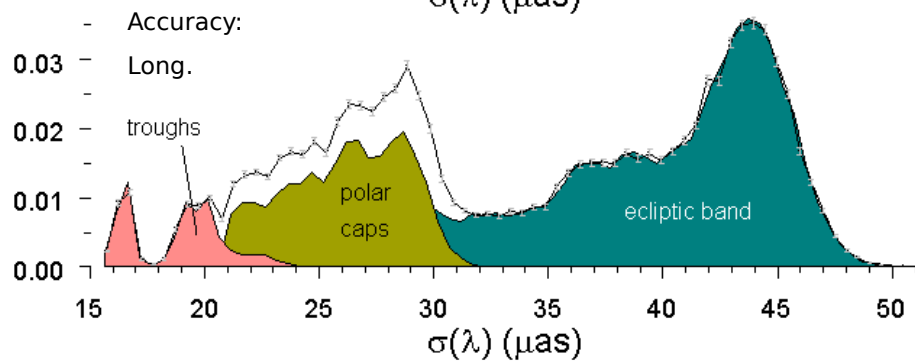
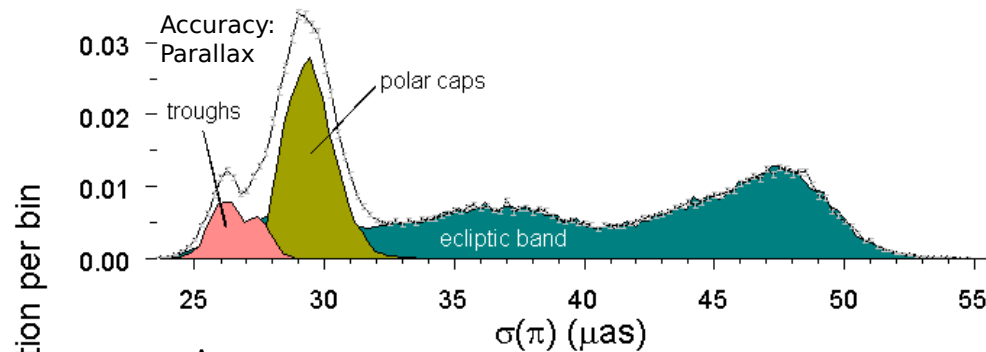
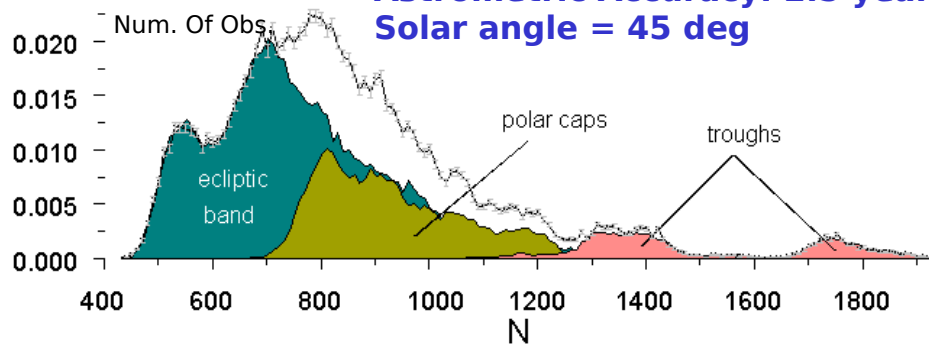
Solar angle Trade Study

Expected number of observations and expected astrometric accuracy as a function of solar angle for 2.5 year mission

	45 Degrees				40 Degrees				35 Degrees			
	Min	Med	Avg	Max	Min	Med	Avg	Max	Min	Med	Avg	Max
Counts	430	808	854	1959	370	799	854	2054	392	762	854	2362
Parallax	23.4	33.8	36.1	55.0	22.4	35.9	38.1	61.4	20.7	40.3	41.1	68.5
Longitude	15.4	35.0	34.0	51.5	15.3	39.9	37.8	60.0	14.1	46.8	42.8	67.1
Latitude	19.1	27.8	27.9	37.8	20.1	26.8	26.9	37.7	18.6	25.9	26.2	35.2
PM Longitude	20.0	47.9	46.9	73.2	19.1	55.4	52.0	82.0	18.4	64.2	58.9	94.1
PM Latitude	27.5	38.7	38.9	53.6	24.3	37.3	37.6	53.0	25.6	36.1	36.6	51.1

**Minimum, Median, Average, and Maximum
Units μ as and μ as/yr**

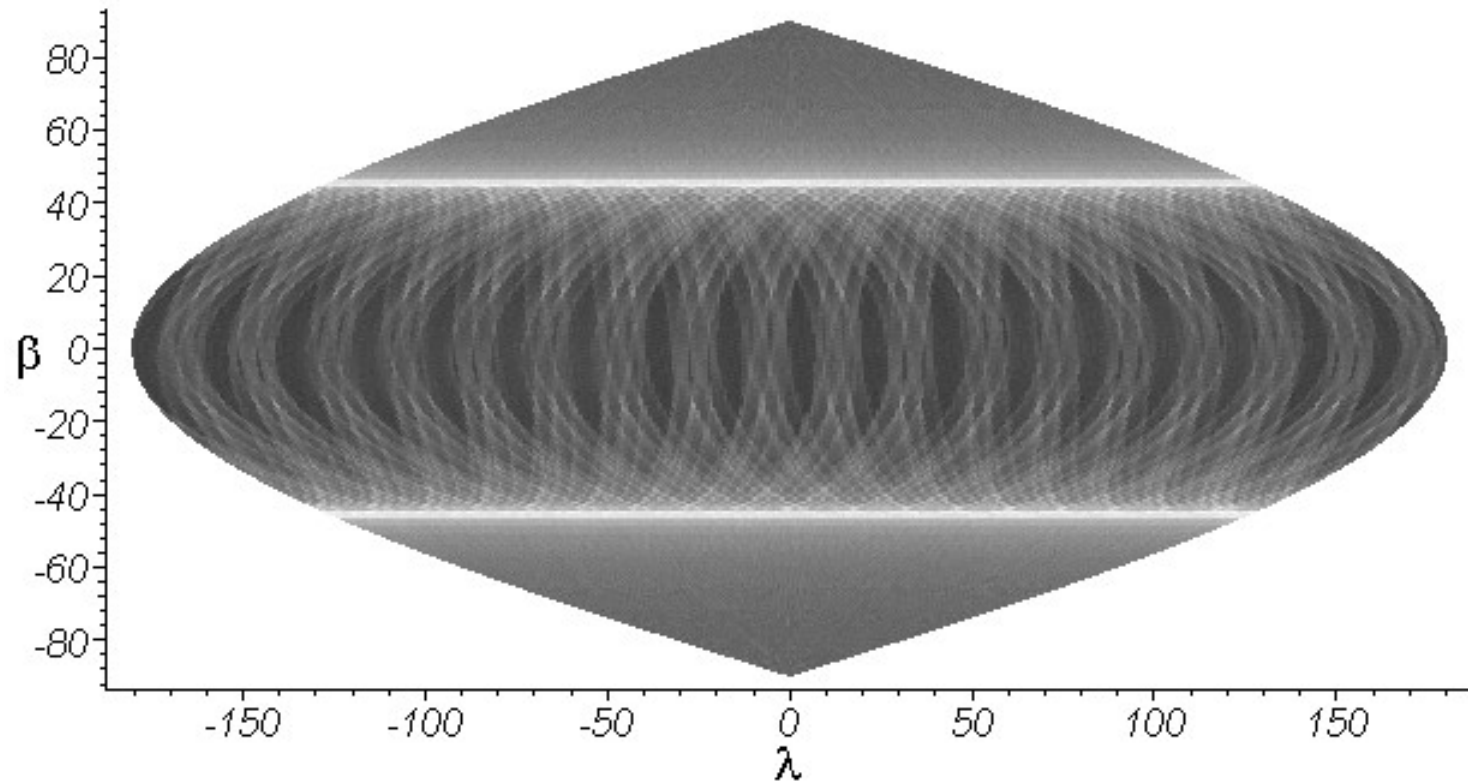
**Astrometric Accuracy: 2.5 year mission,
Solar angle = 45 deg**





FAME Astrometric Accuracy:

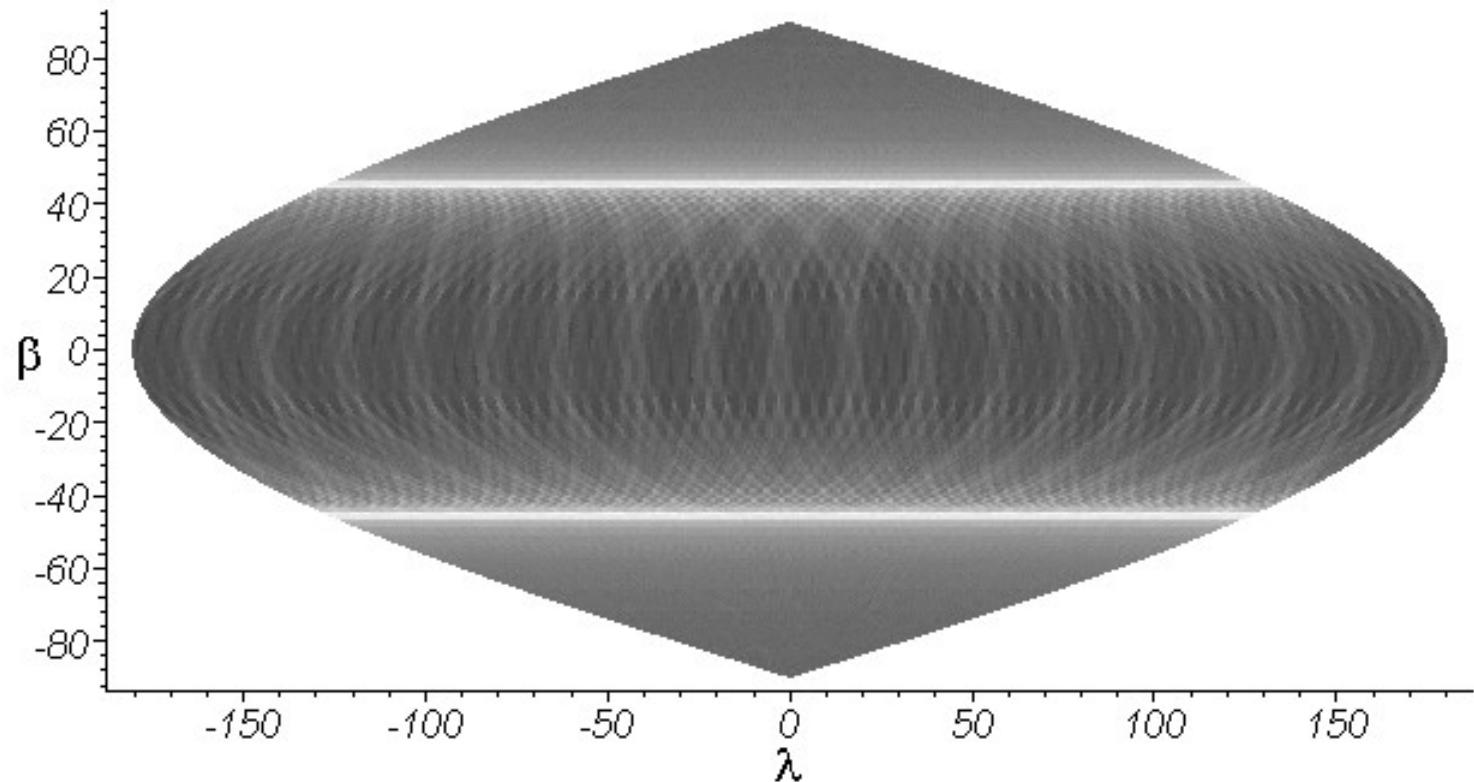
Number of Observations 2.5 year mission, Solar Angle 45°





FAME Astrometric Accuracy:

Number of Observations 5 year mission, Solar Angle 45°





FAME Astrometric Accuracy:

Expected number of observations and expected astrometric accuracy for

~~2.5 year, 5 year mission, with 45° solar angle~~
5-Year Mission

	Min	Med	Avg	Max
Counts	430 1009	808 1600	854 1709	1959 3797
Parallax	23.4 16.5	33.8 23.2	36.1 25.2	55.0 37.2
Longitude	15.4 11.0	35.0 23.7	34.0 23.5	51.5 33.6
Latitude	19.1 15.2	27.8 19.2	27.9 19.2	37.8 22.5
PM Longitude	20.0 7.3	47.9 17.1	46.9 16.5	73.2 24.5
PM Latitude	27.5 9.0	38.7 13.6	38.9 13.5	53.6 17.2

Minimum, Median, Average, and Maximum
Units μ as and μ as/yr



Timeliness of FAME

- ▮ **A major catalog of accurate fundamental stellar properties will enable advances across numerous branches of astrophysics**
- ▮ **FAME will define a reference grid that can be used for SIM, TPF, and space navigation**
- ▮ **FAME will identify interesting targets for SIM and TPF, increasing their scientific return**
- ▮ **FAME is an appropriate stepping stone between Hipparcos and GAIA**
- ▮ **Large CCD array cameras are now routinely built for ground applications and are ready for space**



FAME Summary

- ▮ **Calibrate the zero point of the extragalactic distance scale to 1%**
- ▮ **Determine absolute luminosities of a wide range of spectral types**
- ▮ **Detect a meaningful statistical sample of companion stars, brown dwarfs, and giant planets**
- ▮ **Enable studies of the kinematics of our galaxy, including the effect of dark matter in the disk**
- ▮ **Characterize stellar variability of a large sample of stars at the 0.1% level**
- ▮ **Define an optical reference frame for future scientific endeavors**